

Pergamon *Bk-organic & Medicinal Chemistry*, Vol. 4, No. 9, pp 1421-1427, 1996

Copyright © 1996 Elsevier Science Ltd

Printed in Great Britain. All rights reserved

PII: S0968-0896(96)00136-8 0968-0896/96 \$15.00+0.00

## Structure-Based Design of Parasitic Protease Inhibitors

Rongshi Li/Xiaowu Chen/Baoqing Gong/Paul M. Seizer, b Zhe Li,\* Eugene Davidson, ~

Gary Kurzban/Robert E. Miller," Edwin O. Nuzum, f James H. McKerrow, ~b

Robert J. Fletcher," ~ Sarah A. Gilmore/' ~ Charles S. Craik, a'~ Irwin D. Kuntz,"

Fred E. Cohen a'd and George L. Kenyon a'\*

*Departments" of "Pharmaceutical Chemistry and hPathology, Veterans Affairs Medical Center,*

*~Department of Biochemistry*

*and Biophysics, and aPharmacology and Medicine, Universi~ of California, San Francisco, CA*

*94143-0446, U.S.A.*

*"Department of Biochemistry and Molecular Biolog); Georgetown University, Washington DC 20007, U.S.A.*

*tDivision of Experimental Therapeutics, Walter Reed Army Institute of Research, Washington, DC 20307-5100, U.S.A.*

**Abstract--**To streamline the preclinical phase of pharmaceutical development, we have explored the utility of structural data on

the molecular target and synergy between computational and medicinal chemistry. We have concentrated on parasitic infectious

diseases with a particular emphasis on the development of specific noncovalent inhibitors of proteases that play a key role in the

parasites' life cycles. Frequently, the structure of the enzyme target of pharmaceutical interest is not available. In this setting we

have modeled the structure of the relevant enzyme by virtue of its sequence similarity with proteins of known structure. For

example, we have constructed a homology-based model of falcipain, the trophozoite cysteine protease, and used the computa-

tional ligand identification algorithm DOCK to identify in compuo enzyme inhibitors including oxalic bis(2-hydroxy-1-naphthyl-

methylene)hydrazide (1) [Ring, C. S.; Sun, E.; McKerow, J. H.; Lee, G.; Rosenthal, P. J., Kuntz, I. D.; Cohen, F. E., *Proc. Natl*

*Acad. Sci. U.S.A.* 1993, 90, 3583]. Compound 1 inhibits falcipain ( $IC_{50}$ , 6  $\mu$ M) and the organism in vitro as judged by hypoxanthine

uptake ( $IC_{50}$ , 7  $\mu$ M). Following this lead, to date, we have identified potent bis arylacylhydrazides ( $IC_{50}$  150 nM) and chalcones

( $IC_{50}$  200 nM) that are active against both chloroquine-sensitive and chloroquine-resistant strains of malaria. In a second

example, cruzain, the crystallographically determined structure of a papain-like cysteine protease, resolved to 2.35 Å, was avail-

able. Aided by DOCK, we have identified a family of bis-arylacylhydrazides that are potent inhibitors of cruzain ( $IC_{50}$  600  $\mu$ M).

These compounds represent useful leads for pharmaceutical development over strict enzyme inhibition criteria in a structure-

based design program. Copyright © 1996 Elsevier Science Ltd

### Introduction

More and more successful examples of the design of new ligands based on knowledge of target protein structure have been reported. These include design of noncovalent antiparasitic agents,<sup>1</sup> 3 rational design of sialidase-based inhibitors of influenza virus replication,<sup>4</sup> design of nonpeptide cyclic ureas as HIV protease inhibitors,<sup>5</sup> ~ structure-based discovery of inhibitors of thymidylate synthase,<sup>6</sup> ~ and structure-based design of inhibitors of purine nucleoside phosphorylase.<sup>7</sup> 10 Most structure-based drug design relies on X-ray crystallo-

graphy/NMR spectroscopy" to obtain the appropriate structures to identify new leads and guide lead optimization. Our work on the structure-based drug design of parasitic protease inhibitors has relied upon X-ray crystal structures when available (e.g., cruzain n13 for anti-Chagas disease agents), but has relied on a homology-based model structure if neither X-ray nor NMR data are available (e.g., falcipain for antimalarials) to generate leads and guide our lead optimization. Proteases are involved in many important biological processes including protein turnover, blood coagulation, complement activation, hormone processing, and cancer cell invasion.<sup>1</sup> Thus, they are frequently chosen as targets for drug design and discovery. A potential strategy for the treatment of diseases caused by parasites is the design of compounds which selectively inhibit enzymes that are pivotal for survival of the parasite within the host that are part of biochemical pathways that are specific to the parasite. Parasite proteases are attractive target enzymes because of their roles in replication, metabolism, survival and pathology.<sup>~7</sup>

In the most simple terms, structure-based drug design methods identify favorable and unfavorable interactions between a potential inhibitor and target receptor and maximize the beneficial interactions to increase binding affinity. Although X-ray crystallography continues to be the source of high-resolution information about protein structures, considerable delays often exist between determining the sequence of a protein and solving its structure. Difficulties in protein expression and more commonly in protein crystallization are often responsible for such delays. Currently, no general method exists to predict tertiary structure from amino acid sequences. However, when a protein target is relatively highly homologous to another protein or group of proteins of known structure, a sensible model structure can be proposed. ~s

1421  
1422 R. Li et al.

The World Health Organization estimates that 280 million people are infected with malaria ~9 and 1-2 million deaths are reported annually. 2° While various classes of antimalarial agents are available, chloroquine and its derivatives remain the mainstay of therapy against malaria. Unfortunately, the emergence of malarial parasite strains resistant to chloroquine has eroded its efficacy.<sup>1</sup> This increases the urgency of the search for novel and cost-effective agents to treat chloroquine-resistant malaria.

Chagas disease is caused by *Trypanosoma cruzi*, a protozoan parasite that afflicts more than 24 million people in South and Central America. It is the leading cause of heart failure in many Latin American countries. Currently, there is no satisfactory treatment for this parasitic infection. Cruzain, the major cysteine

protease present in *T. cruzi*, is pivotal for the development and survival of the parasite within the host cells. This makes the enzyme a target for potential trypanocidal drugs.

In our previous reports, 1-3 we described a structure-based approach to inhibitor design for antimalarial drug development using models of falcipain, a malaria trophozoite cysteine protease structure. Here, we summarize our progress to date in the structure-based drug design of parasitic protease inhibitors.

## Results and Discussion

### Lead discovery and optimization

A structure for the malaria cysteine protease, falcipain, was proposed using the X-ray structures of papain and actinidin, two cysteine proteases from plant sources, as a basis for homology modeling? Falcipain has 33% sequence identity with both papain and actinidin. Moreover, ~60% of the conserved sequence centers around the active site regions. The homology-based model of the enzyme provides the template and the DOCK 2.2 algorithm calculates a set of spheres with approximately atom sized radii to fill the active site cleft. Within DOCK, the quality of a given compound's fit into the binding cleft can be evaluated based on its shape complementarity (contact score) or molecular mechanics interaction energy (AMBER force-field score).

The model structure was then used as a template for a DOCK search of the Fine Chemicals Directory of commercially available small molecules for putative ligands (the Fine Chemicals Directory distributed by Molecular Design Limited Information System, San Leandro, California, is currently known as the Available Chemical Directory). When searching a database of compounds, DOCK examines only the 'best' orientation of the small molecule within the binding cleft (DOCK database screening mode). When a single compound is studied, multiple possible binding modes can also be examined (DOCK single mode). Of course, the initial orientation of the compound is dictated in part by the irregular lattice of sphere centers identified originally. To overcome some of the scoring distortion that this bias could impart, a rigid body minimization algorithm has been developed to move the ligand within the binding cleft and optimize the shape or forcefield scores. 23 Compound 1 [oxalic bis((2-hydroxy-1-naphthylmethylene)hydrazide)] was selected based on its score for shape complementarity. Thirty-one compounds were finally tested and a lead compound 1 was identified as the best inhibitor of the protease. The IC<sub>50</sub> value for enzyme inhibition against the substrate benzyloxycarbonyl-Phe-Arg-(7-amino-4-methylcoumarin) was 6  $\mu$ M. 3 More importantly, this compound inhibits the growth of parasites in culture. Malaria lacks some of the enzymes required for *de novo* purine biosynthesis and thus depends on purine salvage

pathways for DNA replication. Compound 1 inhibits parasite growth as judged by its ability to block hypoxanthine uptake, with an apparent IC<sub>50</sub> value of 7 pM.<sup>3</sup> Compound 1 fits a model of the active site of the malarial cysteine protease as shown in Figure 1. 1-3 The DOCK 22 program placed this lead compound 1 into the enzyme's active site, presumably filling three of the substrate side-chain specificity pockets (subsites \$2, \$1' and to a lesser extent \$a). Beginning with compound 1 as shown in Scheme 1, the following chemical modifications were made in an attempt to identify more active agents: (i) The length of the backbone linking the aromatic rings of 1 was shortened via the construction of asymmetric acylhydrazides, which could have less conformational heterogeneity than the symmetric hydrazides, yet still could fill at least two of the three putative subsites (5 in Table 1). Compounds can be constructed by attaching a third aryl group to the center aromatic moiety to fill all three putative subsites (6 in Table 1). (ii) Heterocyclic acylhydrazides were generated by incorporating nitrogen atoms into aromatic rings both to improve water solubility of the compounds and potentially to enhance electrostatic interactions with His67 in the \$2 site. (iii) To increase the chemical/metabolic stability of the compounds, a four-atom hydrazide linker was replaced with a three-atom  $\alpha,\beta$ -unsaturated ketone bridge (7 and 8 in Table 1). (iv) Naphthalene, quinoline or isoquinoline rings were exchanged for substituted phenyl rings on both acylhydrazide and  $\alpha,\beta$ -unsaturated ketone linkers to explore the effective size and electronic character of the putative subsite specificity pocket.

#### **Chemistry, antiparasitic activity and inhibition specificity**

Since cost of production is a critically important consideration if the resulting antimalarials and other antiparasitic agents are ever to be developed into therapeutic agents for the world's developing countries, one of our guidelines for the development of antiparasitic agents is that these compounds should be inexpensive to produce. Hence, we developed relatively simple chemistry to prepare both arylacylhydrazide and chalcone derivatives. For both series, the final step is the condensation of an aldehyde with either acylhydrazines via imine formation 2 or substituted methylketones

Parasitic protease inhibitors 1423

via a Claisen-Schmidt condensation. 1 Since there are a variety of commercially available aldehydes and methylketones as starting materials, a large number of target compounds can be produced relatively inexpensively. For preparation of the key acylhydrazine intermediates, a published procedure was followed)

After some 400 bis arylacylhydrazide and chalcone derivatives were synthesized, they were screened against three different antiparasitic screening systems. Antimalarial activities were evaluated based on an

assay of parasitemia of red blood cells quantitated by a fluorescence-activated cell sorter (FACS) analysis<sup>24</sup> and the more classical assay of metabolic viability, hypoxanthine uptake,<sup>1</sup> described below.

For the FACS analysis, synchronized trophozoite-stage parasites were cultured in human blood at various inhibitor concentrations. The parasites were allowed to mature, the host cell was lysed and parasite invasion of

Figure 1. A putative binding orientation of the 'lead' compound (1) bound to the active site of the malarial cysteine protease. Key residues and

the binding subsites of the protease are colored as cyan (S<sub>1</sub> site), yellow (S<sub>2</sub>/catalytic site), and purple (S<sub>3</sub>/site). For the lead compound, carbon

is shown in green, oxygen in red, and nitrogen in blue.

1424 R. L~ et al.

flesh red blood cells was investigated. Using propidium iodide to stain DNA, the FACS can discriminate between infected and uninfected cells and between stages of intraerythrocytic parasite development as only infected red blood cells contain DNA.<sup>24</sup> The hypoxanthine uptake system assessed the intrinsic antimalarial activity in vitro against the erythrocytic asexual life cycle (blood schizontocides). Two *Plasmodium falciparum* clones, CDC/Indochina III (W2) and CDC/Sierra Leone I (D6),<sup>25</sup> were used for all anti-malarial assays. W2 is resistant to chloroquine, quinine, and pyrimethamine and susceptible to mefloquine. D6 is resistant to mefloquine and susceptible to chloroquine, quinine and pyrimethamine. The resistance indexes are defined as ratios of the IC<sub>50</sub> of a compound against W2 to the IC<sub>50</sub> of the same compound against D6. This index is used as a factor to evaluate whether or not novel antimalarials are potential agents against chloroquine-resistant parasites. Chloroquine and mefloquine were used as controls in the assays. The third screening system involved the assay of two cysteine proteases, cruzain and cathepsin B. ~ Enzymatic activity of these two proteases was measured by following the cleavage of fluorogenic substrates. Structure-activity relationships (SAR) for some bis arylacylhydrazide and chalcone derivatives were reported previously,<sup>22</sup> Here, we summarize antiparasitic activity and enzyme inhibition of a group of hydrazide and chalcone derivatives. As shown in Table 1, the lead compound 1 showed little specificity in both antimalarial activity and enzyme inhibition. Cathepsin B is a mammalian cysteine protease from bovine spleen with 87% sequence identity to a human cathepsin B and papain is a cysteine protease from papaya. For comparison, inhibition activities of both cathepsin B and papain by hydrazide and chalcone derivatives are included in Table 1. Compound 2 is a more specific inhibitor of cruzain, with an IC<sub>50</sub> value of 600 nM, than the rest of the compounds shown in Table 1.

Compound 5 is the best in vitro antimalarial found in the acylhydrazide series with an IC<sub>50</sub> value of 150 nM. The most noteworthy example is compound 6. The IC<sub>50</sub> value as an antimalarial is 450 nM while the IC<sub>50</sub> value as a cathepsin B inhibitor is at least 400-fold higher (Table 1). This suggests that compound 6 is a more

specific inhibitor of the malarial cysteine protease and will be less likely to be toxic to the host. Compound 7 is the best in vitro antimalarial compound found in the chalcone series to date with an IC<sub>50</sub> value of ~ 200 nM. The differences in inhibitory specificity shown above may stem from the fact that the active site residues of these cysteine proteases are quite different, as shown

H

,~ N'~. N N~ N.'~

H

(1)

I vary size of rings

vary size of linker

H ~ O R

improve water solubility

o

Y< H '~z,;~"- OR~

RZ ~ vary size of rings

R 3 ~ RI O .OR6

R~" JR 5 v H "~z~OR7

RI--R 5 = H, OH, OCH<sub>3</sub>, N(CH<sub>3</sub>)<sub>2</sub>

R6, R7 = H, CH<sub>3</sub>

Scheme 1. Lead' optimization by chemical modification.

change

original lead

found by DOCK

R1 = H, OH, OCH<sub>3</sub>

R 2 = H, OH, OCH<sub>3</sub>

R 3 = H, OH, OCH<sub>3</sub>

R4= H, Cl

R5 = H, CH<sub>3</sub>

R6 = H, CH<sub>3</sub>, CH<sub>2</sub>Ar

X, Y or Z=N or CH

X~. RI ~Z ~,~...~ R6

Y-f~' 6 R~

R4

vary size of rings X, Y or Z = N or CH

R2 R

R3~RI/£ RI0~ R8

R 4 ~ R 7

R 5 O R6

RI--R1o = H, F, Cl, Br, NO<sub>2</sub>, CF<sub>3</sub>, OH, OCH<sub>3</sub>, N(CH<sub>3</sub>)<sub>2</sub>

R~ = H, CH<sub>3</sub>

to N-containing heterocycles

I improve metabolic stability

R1 = H, Cl, OH, OCH<sub>3</sub>

R2 = H, Cl, OH, OCH<sub>3</sub>

R 3 = H, CH<sub>3</sub>

R4=H, Cl

R5 = H, OCH<sub>3</sub>

R6 = H, OCH<sub>3</sub>, imidazole

Parasitic protease inhibitors 1,125

in Table 2, especially the residues from the S1S3 site and part of the Sdcatalytic site. The most likely binding orientations of inhibitors involve extensive interactions between inhibitor molecules and the three binding subsites. The highly conserved S1' and catalytic binding

subsites provide basic interactions for binding, while the diverse residue types in the S1/S3 binding subsite among different proteases result in binding specificity. A thorough discussion of structural implications of binding specificity will be presented in a separate manuscript. '~

## Conclusions

Structure-based drug design typically depends upon the experimental determination of the target structure by either X-ray crystallography or NMR spectroscopy. We have circumvented this step and relied exclusively on the amino acid sequence homology between the

**Table 1.** Antiparasitic activity and enzyme inhibition of some hydrazide and chalcone derivatives

Compds Structure Antimalarial Cruzain b Cathepsin Papain ~' activity B"

1 ~ . ~ @ 7 ..... ' 0 (1) 22 (1) 19 (1)

% :', ~" ~, ~, ~ 91 (20) 78 (20) 74 (2(1)

2 ( ~ ' ~ " ~ ~ - 0.6 ~ 20' 50'

4 > 10' 30' 20'

' ~ ~ ND NO ND

6 ~o 2.( ) ~ 200' ND

7 ND ND ND

> 1&

ND ~

ND

0.15(J ~' ~ 2

(i.450 ~, . r.. ~

o. : 3 0 .....

~ ~ 0.19@ ,,,,

8 i 0.. 10 .... 0 (1) 3 (1

0.720 ~, ~

6(1)

"FACS assay. IC~, in j.iM.

~% Enzyme inhibition 0.1M inhibitor).

~ND: not determined.

aHypoxanthine uptake assay, IC~, of W2 (chloroquine-resistance strain) in laM.

"Hypoxanthine uptake assay, IC~, of D6 (chh)roquine-sensitive strain) in laM.

'IC~. In I~M.

malaria enzyme and other cysteine proteases of known structure to support our antimalarial program. A

homology based model of the malaria enzyme served as the template for a computer-based ligand docking calculation that identified a useful lead compound for a

group of cysteine proteases in our antiparasitic

program. Lead optimization was achieved by a

combined approach of computational and synthetic

analysis. Derivatives of the lead were first optimized

for fit using the computer docking program, and then

numerous candidate compounds were synthesized and

tested experimentally. Despite the lack of a detailed

experimental structure of the target enzyme or the

enzyme-inhibitor complex, we have been able to

identify compounds with increased potency. To date,

we have identified a potent bis arylacylhydrazide, 5

(IC<sub>50</sub> 150 nM), and a chalcone, 7 (IC<sub>50</sub> ~200 nM), that

are active against both chloroquine-sensitive and chlor-

oquine-resistant strains of malaria. Due to the ~30% sequence identity between cruzain and falcipain, a subgroup of compounds generated in the malaria project (selected using DOCK as a guide) were also screened against cruzain. The best cruzain inhibitor so far, hydrazide 2, had an  $IC_{50}$  value of 600 nM.

#### Experimental

Melting points were measured on a Thomas-Hoover Unimelt apparatus and are uncorrected. TLC (silica gel 60 GF254, Merck, Darmstadt) was used to monitor reactions and check product homogeneity. NMR spectra at 300 MHz for  $^1H$  and 75 MHz for  $^{13}C$  (tetramethylsilane as internal standard) were recorded on a General Electric QE-300 spectrometer. Chemical ionization mass spectrometry (CIMS) spectra were obtained at the UCSF Mass Spectrometry Facility, A. L. Burlingame, Director. Elemental analyses were performed by the University of California, Berkeley, Microanalytical Laboratory and were within  $\pm 0.4\%$  of the theoretical values. All starting materials were purchased from Aldrich Chemical Company, Inc.

#### General procedure for condensation of aldehyde with hydrazine (Method A for 2 - 6)

To a solution of the aldehyde (1 mmol) in methanol (20 mL) was added the corresponding acylhydrazine (1 mmol). The resulting mixture was heated at reflux at 65 °C for 3 h. In most cases, a precipitate was observed after 10 min. The precipitate was filtered, washed with

Table 2. Active site residues of cysteine proteases  
SI S~/catalytic site 82/3

Proteases 19 177 175 25 159 67 68 69 133 160 205 207  
Papain Gin Trp Ash Cys His Tyr Pro Trp Val Ala Set Phe  
Actinidin ---' - - - - - lie Thr Ala - - Met Ser  
Falcipain . . . . . His - - Phe Asn Ser Glu - -  
Cruzain . . . . . Leu Met Asn Ala Gly Glu Ser  
Cathepsin B . . . . . Glu - - Ser Ala - - Glu Val

"Same residue wpe as papain..

1426 R. LJ et al.

hot methanol (50 mL) and dried under vacuum to give a solid (usually yellow). If needed, additional purification was performed by recrystallization using appropriate solvents.

#### Preparation of acylhydrazines from the corresponding acid or ester (Method A1)

A mixture of the acid (10 mmol) and concd  $H_2SO_4$  (5 mL) in MeOH (25 mL) was heated at reflux for 12-24 h. The mixture was poured onto ice (100 mL). The resulting precipitates were collected, washed with  $H_2O$  and recrystallized from EtOH: $H_2O$  to give the pure methyl ester. The methyl ester was then dissolved in EtOH (80 mL) and treated with hydrazine monohydrate (5.01 g, 100.0 mmol). The resulting mixture was stirred overnight at 20°C and then concentrated to give the corresponding acylhydrazine, which was further purified by recrystallization from EtOH/ $H_2O$ . Compound 1 [oxalic bis(2-hydroxy-1-naphthylmethyle-  
ne)hydrazide] was reported previously. 2 Chalcone



derivatives 7 [1-(2,5-dichlorophenyl)-3-(4-quinolinyl)-2-propen-1-one] and 8 [1-(3,4-dimethoxyphenyl)-3-(3-(2-chloroquinolinyl))-2-propen-1-one] were prepared via a Claisen-Schmidt condensation also described previously)

**2'-Hydroxy-6'-methoxynaphthylacetyl-(2-hydroxy-1-naphthylmethylene)hydrazide (2).**

A 70% yield; mp >280 °C;  $^1\text{H}$  NMR (DMSO- $d_6$ ):  $\delta$  12.84 (s, 1 H), 12.20 (br s, 1 H), 11.20 (br s, 1 H), 9.59 (s, 1 H), 8.46 (s, 1 H), 8.36 (d, 1 H,  $J$ =8.4 Hz), 7.96 (d, 1 H,  $J$ =9.0 Hz), 7.91 (d, 1 H,  $J$ =8.1 Hz), 7.74 (d, 1 H,  $J$ =9.0 Hz), 7.63 (t, 1 H,  $J$ =6 Hz), 7.43 (t, 1 H,  $J$ =7.5 Hz), 7.28 (d, 1 H,  $J$ =9.0 Hz), 7.22 (dd, 1 H,  $J$ =2.0, 9.1 Hz), 3.90 (s, 3 H);  $^{13}\text{C}$  NMR (DMSO- $d_6$ ):  $\delta$  163.08, 158.14, 155.73, 152.16, 147.48, 132.89, 131.71, 131.48, 129.25, 128.93, 127.81, 127.76, 127.72, 127.44, 123.56, 121.31, 121.00, 119.94, 118.21, 110.94, 108.65, 106.45, 55.17; CIMS:  $m/z$  (MH $^+$ ) 387.3. Anal. (C<sub>23</sub>H<sub>18</sub>N<sub>2</sub>O<sub>4</sub>): calcd: C, 71.49; H, 4.70; N, 7.25. Found: C, 71.09; H, 4.84; N, 7.23%.

**2'-Hydroxynaphthylacetyl-(2, 8-dihydroxy-1-naphthylmethylene)hydrazide (3).**

A 88% yield; mp 274 °C (dec);  $^1\text{H}$  NMR (DMSO- $d_6$ ):  $\delta$  14.03 (s, 1 H), 12.54 (br s, 1 H), 11.31 (br s, 1 H), 10.47 (s, 1 H), 10.37 (s, 1 H), 8.53 (s, 1 H), 7.96 (d, 1 H,  $J$ =8.1 Hz), 7.87 (d, 1 H,  $J$ =9.0 Hz), 7.80 (d, 1 H,  $J$ =8.4 Hz), 7.54 (t, 1 H,  $J$ =7.5 Hz), 7.39 (m, 3 H), 7.22 (m, 2 H), 7.08 (d, 1 H,  $J$ =7.2 Hz);  $^{13}\text{C}$  NMR (DMSO- $d_6$ ):  $\delta$  163.80, 159.39, 154.34, 153.30, 153.02, 135.93, 133.51, 130.26, 130.06, 128.66, 128.28, 126.73, 125.91, 123.82, 123.71, 121.72, 120.50, 119.80, 119.43, 112.51, 110.67, 108.87; CIMS:  $m/z$  (MH $^+$ ) 373.3. Anal. (C<sub>21</sub>H<sub>16</sub>N<sub>2</sub>O<sub>4</sub>·0.2H<sub>2</sub>O): calcd: C, 70.28; H, 4.40; N, 7.45. Found: C, 70.45; H, 4.58; N, 7.40%.

**2'-Hydroxynaphthylacetyl-(2, 5-dihydroxy-1-naphthylmethylene)hydrazide (4).**

A 74% yield; mp >280 °C;  $^1\text{H}$  NMR (DMSO- $d_6$ ):  $\delta$  12.81 (s, 1 H), 12.23 (s, 1 H), 11.29 (s, 1 H), 10.22 (s, 1 H), 9.52 (s, 1 H), 8.52 (s, 1 H), 8.20 (d, 1 H,  $J$ =9.2 Hz), 7.59 (d, 1 H,  $J$ =8.1 Hz), 7.80 (d, 1 H,  $J$ =8.2 Hz), 7.71 (d, 1 H,  $J$ =8.6 Hz), 7.54 (t, 1 H,  $J$ =7.5 Hz), 7.41 (m, 3 H), 7.16 (d, 1 H,  $J$ =9.2 Hz), 6.80 (d, 1 H,  $J$ =7.5 Hz);  $^{13}\text{C}$  NMR (DMSO- $d_6$ ):  $\delta$  163.04, 158.38, 154.10, 153.89, 148.09, 135.93, 133.39, 130.52, 128.66, 128.52, 128.32, 127.01, 126.78, 125.84, 123.85, 119.84, 118.93, 117.08, 111.40, 110.60, 108.29, 106.46; CIMS:  $m/z$  (MH $^+$ ) 373.2. Anal. (C<sub>22</sub>H<sub>16</sub>N<sub>2</sub>O<sub>4</sub>·0.5H<sub>2</sub>O): calcd: C, 69.28; H, 4.49; N, 7.35. Found: C, 69.35; H, 4.54; N, 7.27%.

**2',4'-Dihydroxyphenylacetyl-(2-hydroxy-1-naphthylmethylene)hydrazide (5).**

A 81% yield; mp >280 °C;  $^1\text{H}$  NMR (DMSO- $d_6$ ):  $\delta$  12.83 (s, 1 H), 12.18 (br s, 1 H), 12.01 (br s, 1 H), 10.35 (br s, 1 H), 9.54 (s, 1 H), 8.32 (d, 1 H,  $J$ =8.6 Hz), 7.88 (m, 3 H), 7.62 (t, 1 H,  $J$ =7.6 Hz), 7.42 (t, 1 H,  $J$ =7.4 Hz), 7.26 (d, 1 H,  $J$ =8.9 Hz), 6.47 (d, 1 H,  $J$ =8.8 Hz), 6.43 (s, 1 H);  $^{13}\text{C}$  NMR

(DMSO-d<sub>6</sub>):  $\delta$  164.58, 162.94, 161.90, 158.02, 146.90, 132.72, 131.67, 129.96, 128.94, 127.80, 127.71, 123.54, 120.87, 178.92, 108.66, 107.78, 106.14, 102.93; CIMS:  $m/z$  (MH<sup>+</sup>) 323.1. Anal. (C<sub>18</sub>H<sub>14</sub>N<sub>2</sub>O<sub>4</sub>): calcd: C, 67.08; H, 4.38; N, 8.69. Found: C, 67.04; H, 4.53; N, 8.91%.

**2' - Hydroxy-4' - (4-nitrobenzyloxy) phenylacyl- (2,4-dihydroxy-1-naphthylmethylene)hydrazide (6).** A 91% yield; mp >270 °C; <sup>1</sup>H NMR (DMSO-d<sub>6</sub>):  $\delta$  12.82 (s, 1 H), 12.46 (br s, 1 H), 11.90 (br s, 1 H), 11.03 (br s, 1 H), 9.39 (s, 1 H), 8.25 (d, 1 H, J=8.1 Hz), 8.17 (d, 1 H, J=8.6 Hz), 8.10 (d, 1 H, J=8.3 Hz), 7.91 (d, 1 H, J=8.8 Hz), 7.71 (d, 1 H, J=8.2 Hz), 7.58 (t, 1 H, J=7.6 Hz), 7.34 (t, 1 H, J=7.5 Hz), 6.91 (d, 1 H, J=8.8 Hz), 6.61 (s, 1 H), 6.60 (s, 1 H), 5.33 (s, 2 H); <sup>13</sup>C NMR (DMSO-d<sub>6</sub>):  $\delta$  164.23, 162.47, 162.10, 160.37, 157.62, 147.94, 147.07, 144.41, 132.92, 129.41, 128.27, 128.27, 123.66, 123.66, 122.93, 122.50, 120.67, 120.28, 107.75, 107.10, 102.39, 101.34, 100.46, 68.23; CIMS:  $m/z$  (MH<sup>+</sup>) 474.2. Anal. (C<sub>25</sub>H<sub>19</sub>N<sub>3</sub>O<sub>7</sub>·2/3H<sub>2</sub>O): calcd: C, 61.85; H, 4.12; N, 8.66. Found: C, 61.77; H, 4.33; N, 8.67%.

#### Biological assays

The previously published FACS assay protocol was followed for in vitro antimalarial testing. 24 Hypoxanthine uptake and enzyme (cruzain, cathepsin B and papain) inhibition procedures were also published previously?

#### Acknowledgments

This work was supported by grants from the Advanced Research Projects Agency (MDA-972-91-J1013; N00014-90-2032), the National Institute of Allergy and Infectious Disease (P01AI35707) and the World Health Organization (WHO 940104). The authors thank Margaret Brown from the Department of Veterans Affairs Medical Center, San Francisco, for excellent technical assistance.

Parasitic protease inhibitors 1427

#### References

1. Li, R.; Chen, X.; Gong, B.; Dominguez, J. N.; Davidson, E.; Kurzban, G.; Miller, R. E.; Nuzum, E. O.; Rosenthal, P. J.; McKerrow, J. H.; Kenyon, G. L.; Cohen, F. E. *J. Med. Chem.* 1995, 38, 5031.
2. Li, Z.; Chen, X.; Davidson, E.; Zwang, O.; Mendis, C.; Ring, C. S.; Roush, W. R.; Fegley, G.; Li, R.; Rosenthal, P. J.; Lee, G. K.; Kenyon, G. L.; Kuntz, I. D.; Cohen, F. E. *Chem. Biol.* 1994, 1, 31.
3. Ring, C. S.; Sun, E.; McKerrow, J. H.; Lee, G.; Rosenthal, P. J.; Kuntz, I. D.; Cohen, F. E. *Proc. Natl Acad. Sci. U.S.A.* 1993, 90, 3583.
4. von Itzstein, M.; Wu, W.-Y.; Kok, G. B.; Pegg, M. S.; Dyason, J. C.; Jin, B.; Phan, T. V.; Smythe, M. L.; White, H. F.; Oliver, S. W.; Colman, P. M.; Varghese, J. N.; Ryan, D. M.; Woods, J. M.; Bethell, R. C.; Hotham, V. J.; Cameron, J. M.; Penn, C. R. *Nature (London)* 1993, 363, 418.
5. Lam, P. Y. S.; Jadhav, P. K.; Eyermann, C. J.; Hodge, C.

- N.; Ru, Y.; Bacheler, L. T.; Meek, J. L.; Otto, M. J.; Rayner, M. M.; Wong, Y. N.; Chang, C.-H.; Weber, P. C.; Jackson, D. A.; Sharpe, T. R.; Erickson-Viitanen, S. *Science* 1994, 263, 380.
6. Shoichet, B. K.; Stroud, R. M.; Santi, D. V.; Kuntz, I. D.; Perry, K. M. *Science* 1993, 259, 1445.
7. Montgomery, J. A.; Niwas, S.; Rose J. D.; Secrist, III, J. A.; Babu, Y. S.; Bugg, C. E.; Erion, M. D.; Guida, W. C.; Ealick, S. E. *J. Med. Chem.* 1993, 36, 55.
8. Secrist, III, J. A.; Niwas, S.; Rose, J. D.; Babu, Y. S.; Bugg, C. E.; Erion, M. D.; Guida, W. C.; Ealick, S. E.; Montgomery, J. A. *J. Med. Chem.* 1993, 36, 1847.
9. Erion, M. D.; Niwas, S.; Rose J. D.; Ananthan, S.; Allen, M.; Secrist, III, J. A.; Babu, Y. S.; Bugg, C. E.; Guida, W. C.; Ealick, S. E.; Montgomery, J. A. *J. Med. Chem.* 1993, 36, 3771.
10. Guida, W. C.; Elliott, R. D.; Thomas, H. J.; Secrist, III, J. A.; Babu, Y. S.; Bugg, C. E.; Erion, M. D.; Ealick, S. E.; Montgomery, J. A. *J. Med. Chem.* 1994, 37, 1109.
11. Fesik, S. W. *J. Biomol. NMR* 1993, 3, 261.
12. McGrath, M. E.; Eakin, A. E.; Engel, J. C.; McKerrow, J. H.; Craik, C. S.; Fletterick, R. *J. J. Mol Biol.* 1995, 247, 251.
13. Chen, X.; Li, R.; Gong, B.; Davidson, E.; Dominguez, J. N.; McKerrow, J. H.; Kenyon, G. L.; Cohen, F. E. manuscript in preparation.
14. Stryer, L. *Biochemistry*; Freeman: New York, 1988.
15. Thomas, L.; Leduc, R.; Thorne, B. A.; Smeekens, S. P.; Steiner, D. F.; Thomas, G. *Proc. Natl. Acad. Sci. US*, 4, 1991, 88, 5297.
16. Cohen, R. L.; Xi, X. P.; Crowley, C. W.; Lucas, B. K.; Levinson, A. D.; Shuman, M. A. *Blood* 1991, 72, 479.
17. McKerrow, J. H.; Sun, E.; Rosenthal, P. J.; Bouvier, J. *Annu. Rev. Microbiol.* 1993, 47, 821.
18. Ring, C. S.; Cohen, F. E. *FASEB J.* 1993, 7, 783.
19. Gibbons, A. *Science* 1992, 256, 1135.
20. Walsh, J. A. *Ann. N. Y. Acad. Sci.* 1989, 569, 1.
21. World Health Organization Malaria Action Program. *Trans. R. Trop. Med. Hyg.* 1986, 80, 1.
22. Kuntz, I. D. *Science* 1992, 257, 1078; DOCK V 3.0 was used in all initial phases of this work. The current release is DOCK V 3.5. Contact I.D. Kuntz for distribution information.
23. Meng, E. C.; Gschwend, D. A.; Blaney, J. M.; Kuntz, I. D. *Proteins* 1993, 17, 266.
24. Clark, D. L.; Chrissey, L. A.; Campbell, F. R.; Davidson, E. A. *Molec. Biochem. Parasitol.* 1994, 63, 129.
25. Oduola, A. M.; Weatherly, N. F.; Bowdre, J. H.; Desjardins, R. E. *In Vitro. Exp. Parasitol.* 1988, 66, 86.

(Received in U.S.-4. 3 October 1995)